Position Paper

"I simply didn't think, ok?"

Some reflections on the quality of scientific research

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1. **Introduction**
2. **Quality and truth: Feynman, Dirac and the character of physical laws**
3. **Quality and fitness for purpose: thinking, knowing and the ethical box of Los Alamos**
4. **From Los Alamos to NASA**
5. **Quality, reliability and safety: the Challenger disaster**
6. **Quality and integrity: Cargo Cult Science**
7. **Quality and reflexivity: concluding remarks**

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Abstract. *In this paper, I explore the elusive yet crucial issue of the quality of research, taking the renowned theoretical physicist Richard Feynman as a narrative expedient. The story follows Feynman along two main episodes that mark the transition from curiosity-oriented science to big technoscientific enterprise: the Manhattan Project and the Space Shuttle Challenger disaster. Along the way, I examine the relationship between quality and truth, fitness for purpose and integrity, considering their relevance and limitations. I conclude by reflecting on quality and reflexivity in current times.*

1. Introduction

Developing tools for critical thinking, socio-ecological awareness and engagement is increasingly becoming a primary need of researchers, to better cope with the contemporary – very pressing – systemic crisis, while improving their professional and personal lives.

In the late summer of 2019, I was invited to meet and work on these issues with a group of ecology researchers of the Italian LTER network (Long Term Ecological Research), together with researchers from a variety of related fields, such as the sociology of science and technology, museology and science education, the performing arts and theater in nature, mindfulness and affective ecology.

As a means for collective reflection, I proposed a historical account of how science and technology have been defined and legitimized - i.e. demarcated[1] - over the course of the past three centuries, from the early stages of the scientific and industrial revolution to the contemporary age (pre-Covid 19, see Benessia and Funtowicz, 2016). A variety of figures ranging from scientists of different disciplines to philosophers, sociologists, public officials and entrepreneurs have been contributing to drawing an image of science and technology, by delineating its contours against the background of different socio-economic and political forces. Observing this shape-shifting image along a historical trajectory and realizing how fuzzy, permeable and contingent its boundaries are, engendered a lively discussion on the present condition of researchers. An extensive dialogue was generated about how we could better engage with the ocean of historical precedents and the current, massive socio-economic dynamics, in order to deepen the value of our research, both inside and outside our work environment.

As the days went by and different contributions enriched our collective experience, the elusive and yet crucial issue of the quality of research became more and more pressing, not only in science but also in art, as an overarching pillar of our gathering. How to generate and evaluate it, and in most cases how to retrieve it in the daily deluge of funding constraints, structural bureaucracies, and power dynamics.

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[1] The demarcation of science can be defined as the philosophical drive to define what characterizes science as a form of uniquely privileged kind of knowledge, distinguishing it from all other epistemic endeavors. As an abstract analytical problem, the issue of demarcation has colonized the field of the philosophy of science for more than a century, evolving over time through a dynamical balance of ideological commitments (Ravetz 1991). As a practical problem, it can be defined as the effort to construct and maintain effective boundaries between science and non-science in the pursuit of professional goals, intellectual authority and moral autonomy (Gyerin 1983 and 1999).

During a meal in our gathering I remembered reading that the word "art" has a Sanskrit root, *"ar"*, which means: "to set in motion", "to move forward". I brought this to the attention of the group of scientists and artists I was sitting with. Some fundamental, open questions followed. What do we "set in motion" with our being in the world, as artists, scientists, policy makers – as humans? What do we value as meaningful in our research? How do we collectively foster and evaluate the quality of our creations and discoveries? These issues can be taken as a direction to navigate through the complex predicament we are facing as a species, when both science and democratic governance, the two legitimizing pillars of the quality of our knowledge and action, are faltering (Waltner-Toews *et al.*, 2021).

To explore a single path within the forest of quality, I take in what follows a selection of episodes from the work and life experience of one of the most renowned scientists of modern times, the American, Nobel laureate theoretical physicist Richard Feynman. Living between 1918 and 1988, he crossed the 20th century's technoscientific development and deployment, in all its marvels and horrors, becoming an ideal narrative expedient to reflect on the issue of quality of knowledge (science) and action (technology, decision making) over time. The story is moved forward through a set of quotes by Feynman himself, triggering different approaches to the issue of the quality of research, exploring its relationship with truth, fitness for purpose and integrity from the early 1940s to the late 1980s, a crucial time in the transition from curiosity-oriented science to big, corporate technoscientific enterprise.

Some fruitful ingredients emerge to reconsider the demands for quality of research that permeated our meeting in 2019 and are critical today.

2. Quality and truth: Feynman, Dirac and the character of physical laws

"What do I mean by understanding? Nothing deep or accurate – just to be able to see some of the qualitative consequences of the equations by some method other than solving them in detail." (Feynman, 1947)

The first episode of our story is set in the 1940s, during the Second World War. In 1942, Richard Feynman is in his twenties, a young researcher working on his PhD at Princeton, when he is asked by an older colleague, Robert Wilson, to verify the efficiency of a machine called isotron for the production of enriched uranium. Since the attack on Pearl Harbor, the Unites States are at war and the race to beat Germany in the quest for a nuclear weapon has begun.

A few months later, in 1943, Robert Oppenheimer invites the group working in Princeton to join the Manhattan Project, the American-coordinated effort for the construction of the first atomic device. Feynman manages to finish his PhD before moving to the secret military base of Los Alamos, a semi-desert location not far from Santa Fe, in New Mexico.

As one of the youngest scientists, he is assigned to several different tasks, pushing him to engage with a variety of people and types of work, far from anything he has experienced before. He essentially has to adapt his theoretical approach to the experimental needs, fast pace and multi-disciplinary environment of the Manhattan Project. He is enmeshed in the study of instruments and materials, including the so-called 'Water Boiler' a small nuclear reactor designed to experiment on the fundamental properties of chain reaction. He is dispatched to Oak Ridge, where fissionable substances are produced, to advise plant supervisors on how to handle safely nuclear waste and products. And he is in charge of the numerical calculation of implosion of the plutonium core, having to translate the abstract equations of motion into primary questions such as: How hot, how fast, how much yield?

In all these assignments, he has to communicate and work effectively with a wide range of military personnel, architects, chemical and mechanical engineers, technical personnel, and he is forced to develop a modular way of working that can be of quick and effective use to non-theorists.

In a compelling article on Feynman's work during the war, the historian of science Peter Galison describes the emergence of a specific style of research in the theoretical culture of Los Alamos (Galison, 1998). The science of neutrons, the keystone of the project, is characterized by using building-blocks, in which interchangeable pieces can snap into place, shifting the attention away from the equations of motion and moving it towards the space of solutions.

Fully embedded in the Los Alamos collective endeavor, Feynman chooses to emphasize concepts that are used to express the solutions of specific problems in visual, not formal terms, privileging plausible, not rigorous approximations. In the quantum duality between particles and fields, he favors the particulate, more intuitive, representation. He focuses his attention on the underlying physical processes, building up from the simpler to the more complex, following a bottom-up approach, rather than deducing downward from general equations.

The praxis and methodology that is needed for the mission to proceed as smoothly and quickly as possible ends up informing – and partially matching – Feynman's own character and style of research: the way in which he tackles theoretical problems, the language he is interested in developing and his regard for physical meaning over mathematical form.

In the years from 1947 to 1949, the US National Academy of Sciences sponsors three conferences on the state of theoretical physics, at Shelter Island, Pocono and Oldstone. They are "small, closed and elitist in spirit" and they serve as rituals to cleanse and revitalize the spirit of pure research after the horrors of the war (Schweber 1986). In these conferences Feynman establishes himself as one of the leading physicists of his generation, presenting for the first time, in more and more detail, his later famous diagrams (Feynman, 1949). Part representations and part symbolic signs, the diagrams allow the visualizing and calculating of the dynamics of interactions between light and matter. They focus on elemental scattering processes, primitive pieces of a rule-governed game that can be combined *ad libitum* following some simple pictorial rules. They are built around solutions, simple expressions that "move particles" from point to point. They allow precise computations to be easily performed and they don't depend on explicit logical deductions from the fundamental equations of motions they come from[2].

This overall shift is difficult to accept for one of the initiators of quantum mechanics, the British physicist Paul Dirac. In the late 20s, Dirac formulated the equation that carries his name, as the founding stone of quantum electrodynamics (QED, the technical name for the theory of interaction between light and matter). He was awarded the Nobel Prize for his remarkable work in 1933 with Erwin Schrödinger. As one of the biggest achievements of theoretical physics, the Dirac equation of motion combined for the first time, into a strikingly synthetic and elegant form, the constraints of quantum mechanics and special relativity, describing the motion of electrons and predicting the existence of antimatter. It was the foundation of what is known as quantum field theory, the grammar of contemporary theoretical physics.

In Pocono, Dirac confronts Feynman over what he believes is a drastic departure from the search for fundamental physical laws, to favor, unapologetically, the mere setting up of working rules. Adhering to the founding spirit of Galileo and Newton, for Dirac, the quality of a physical theory has to do with its capacity to uncover the mathematical laws that govern natural phenomena, to unveil some

[2] When confronted directly, these equations presented major obstacles in the form of values diverging to infinity, precluding any physically acceptable result. At the postwar conferences, Feynman and some colleagues from his generation propose a way out of the impasse by absorbing the infinities into a few measurable, physical quantities, shifting the focus from mathematical rigor to physical meaning and quantitative computational success: a procedure named renormalization.

Truth about Nature's inner workings, through a form that appears universal and inevitable – and therefore, in Dirac's terms, beautiful. Empirical accuracy, i.e. experimental truth, is not enough[3]. If the computational rules can't be logically deduced from the equations of motion, they can't be correct.

> It is more important to have beauty in one's equations than to have them fit experiment… It seems that if one is working from the point of view of getting beauty in one's equations, and if one has really a sound insight, one is on a sure line of progress (Dirac, 1963).

Albert Einstein notably expressed this approach to the character of physical laws when he received the first experimental confirmation of his theory of gravitation, after the total solar eclipse of 1919. When asked what he would have done if the results had not confirmed his theory, he famously replied: "Well then I would have been sorry for the dear Lord, because the theory is correct" (Rosenthal-Schneider, 1919).

Leading a whole new generation of American postwar physicists, Richard Feynman is after a different kind of theory, phenomenological and intuitive, that can be routinely computed, even if that means giving up the deductive link from the synthetic universality and elegance of the primary equations of motion. Free spirited and pluralist in his style of research, he enjoys reformulating solutions to physical problems *ab initio*. In his vision, the epistemological value of a theory coincides with its capacity to make sense of physical phenomena, in a quantitative, consistent and accurate way. Its mathematical form and metaphysical implications are less relevant. In other words, the quality of his work is defined in terms of solvability[4] and empirical accuracy. Knowing how to describe and predict the interaction between light and matter in a computable and coherent way is more valuable than pursuing the mathematical, essential elegance of the fundamental laws governing it. In a parallel way to Feynman's diagrammatic theory, two other physicists – Julian Schwinger and Sin-Itiro Tomonaga – developed a formulation of QED expressed in the language of Dirac's equations of motion.

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[3] Here I use Truth, with upper case T, as a way to hint at the top-down, reductionist approach to physics, implying the existence of a single unified theory of everything (ToE) from which the mathematical laws describing all phenomena can be logically deduced. Universal truth and mathematical beauty are strictly entangled in this kind of approach. I use truth, with lower case t, as a way of referring to the empirical accuracy of a physical theory, regardless of its status and form as mathematical law. It is important to remember that Feynman fully endorsed the reductionist approach, but he wasn't attached to any specific formalism.

[4] In this sense, Feynman's style of research anticipates the characterization of science as "The Art of the Soluble" given by the British Nobel-Prized immunologist Paul Medawar two decades later (Medawar, 1967).

Even though the different versions were demonstrated to be equivalent – and earned a Nobel Prize for all three physicists in 1965 – Feynman's diagrams had the appeal of "bringing computation to the masses" (Schwinger, 1982), a different, more accessible kind of mathematical beauty.

3. Quality and fitness for purpose: thinking, knowing and the ethical box of Los Alamos

"I simply didn't think, ok?" (Feynman, 1981)

Before moving along the timeline, let's go back for a moment and look at the blind spot we left on our way, the actual success of the Manhattan project and its appalling consequences.

In May 1945, Germany surrendered and the war seemed to be close to coming to an end. Yet the work at Los Alamos continued. On July 16, the first open-field nuclear detonation, the Trinity Test, was successfully performed. At Los Alamos the event was celebrated as a great achievement. Feynman recalls beating the bongos in the back of a jeep and the general euphoria that permeated that summer night. Only Robert Wilson, the physicist who invited Feynman to work on the project since the beginning, was found moping in a room[5]. When asked why, he replied: "We did a terrible thing" (Feynman, 1975).

Less than a month later, on August 6, 1945, the uranium bomb named Little Boy was dropped on the city of Hiroshima. On August 9, Fat Man, a plutonium bomb very similar to the one tested in July, was detonated in the sky over Nagasaki. The devastating devices worked consistently well, killing instantly hundreds of thousands of people and many more over time, through radiation poisoning.

In an interview given in 1981 to the BBC, Feynman recalls the excitement after the Trinity Test. When asked about the decision to pursue the construction of the bomb even after Germany surrendered, he replies:

> What I did immorally I would say was not to remember the reason that I said I was doing it, so that when the reason changed, when Germany was defeated, not a single thought came to my mind at all about that, that

[5] In an interview given in 1965, featured in a documentary produced by Fred Freed at NBC, Robert Oppenheimer declared that he knew the world would never be the same and he famously evoked in his mind the phrase from the Bhagavad Gita "I am become Death, the destroyer of worlds". Feynman doesn't single out his reaction from the rest of the group. For the extract see: https://www.youtube.com/watch?v=_LmxIptS3cw, Retrieved on June 16, 2021.

> meant now that I had to reconsider why I was continuing to do this. I simply didn't think, ok? (Feynman, 1981).

The relationship between thinking and moral judgment evoked in Feynman's eloquent words was explored at length by the political philosopher Hannah Arendt, who fled from Germany to the United States in 1941. In 1961 Arendt was sent to Jerusalem by the journal "The New Yorker" to document first-hand the trial of the Nazi criminal Adolf Eichmann. In that experience, she was struck by his "terrifying normality", the apparent lack of any particular wickedness or pathology in his personality, other than a "perhaps extraordinary shallowness" and "a quite authentic inability to think" (Arendt, 1971). What she considered as the mere observation of a phenomenon during the trial – the *quaestio facti* famously defined as 'the banality of evil" [6] – led her to reflect in the following years on the *quaestio juris*, the right she had in defining and using the concept. In a series of illuminating lectures written in the 1970s and collected in a posthumous volume called "The Life of the Mind", she focused on the nature and function of thinking, and its relation to moral judgment (Arendt, 1971 and 1978).

> Is our ability to judge, to tell right from wrong, beautiful from ugly, dependent upon our faculty of thought? Do the inability to think and the disastrous failure of what we commonly call conscience coincide?" (Arendt, 1971)

It is difficult to imagine that Richard Feynman, one of the most capable and brilliant mind of the time, was unable to think. What happened then? Some clarifications from Arendt's writing can help us. Human intellectual abilities can be used as instruments for knowing and doing, as was so successfully the case in Los Alamos. Quite differently, the activity of thinking, in itself, as Arendt describes it, has to do with introspection. Like a powerful and uncomfortable wind, it sets knowledge in motion, unfreezes its constituting arguments, the *logoi* in Socratic terms, and leaves nothing behind. It is the movement of thinking, with no particular anchoring to any moral proposition, which creates the premises for awakening human conscience (Arendt, 1971) [7]. Conversely, lack of thinking implies a kind of stillness, in our case stiffness – a moral rigidity that didn't allow to rapidly adjust the course of actions (withdrawing from the program) according to the new available knowledge (the fact that Germany had surrendered).

[6] Arendt's thesis on the banality of evil in the specific context of Eichmann's trial met with strong opposition and outrage, accusing her of not acknowledging the radical evil of Nazi's Final Solution, diminishing it to a narrow, formal argument (Wolfe 2011, White 2018).

[7] Arendt reminds us of the Latin etymology of the word conscience: *co-scire* "to know with and by oneself" (Arendt, 1971).

Not only Feynman, but the entire group of scientists involved in the making of the bomb reacted in the same way: they simply didn't think. How is that possible? In a lecture about his experience at Los Alamos given at the University of California, Santa Barbara in 1975, Feynman recalls:

> You see what happened to me, and what happened to the rest of us, is that we started for a good reason. Then we were working very hard to do something, and to accomplish it was a pleasure, was excitement. And you had to stop thinking, you know, you just stopped. After you thought at the beginning, you stopped thinking (Feynman, 1975).

The Manhattan Project was set up with a very precise mission: building a weapon of incomparable power, a game changer in the war. The moral reason behind the undertaking was explicit and shared: building the bomb before Germany did. The univocally defined aims and motivations were supported by a massive outlay of economic and human resources, in what is considered the first instance of technoscientific enterprise: the advent of the so-called Big Science.

In other words, building the atomic bomb was possible and desirable because it was needed. By endorsing the project, the main actors were therefore immersed not only in the theoretical culture we explored before, but also, and more radically, in an ethical box, perfectly sealed from any wind of thought, along the three orthogonal axes of competence, aspiration and duty. Inside the box, protected by the economic and military organizational machine of the project, the quality of their research (knowledge and action) was measured in terms of its fitness for the purpose of the mission. All other values – and thoughts – were externalized. The perfect detonation and the striking destructive power of the bomb were interpreted consequently, as a great success. Later, when the project was dismissed, the box broke, and a storm of thoughts awoke the conscience of most of the people involved. Feynman describes his experience in these terms:

> I sat in a restaurant in New York for example and I looked out at the buildings. How far away I was thinking, how much the radius of the Hiroshima bomb damage was and so forth… how far from here was 34th Street? …All those buildings, all smashed up and so on. And … I would go along and would see people building a bridge, or making a new road and I thought they're crazy, they just don't understand, they don't understand. Why are they making new things? It's useless (Feynman, 1975).

4. From Los Alamos to NASA

For the next episode we move forty years ahead along the timeline, to land in the middle of the 1980s at the US National Aeronautics and Space Administration (NASA). In four decades, the relationship between science, technology and society has evolved through complex and controversial dynamics, calling for a quick historical overview[8].

In 1942, in opposition to the uprising of fascist and nationalist movements, the American sociologist Robert Merton identifies the unique ability of modern science to provide "certified" knowledge as a result of the institutionalization of distinctive social norms, in the form of a specific *ethos* driving its progress. The ethical and epistemic value ensured by the so-called Mertonian norms – communalism, universalism, disinterestedness, and organized skepticism – contribute to defining the modern ideal of the "republic of science": an autonomous community of peers, self-governed through shared knowledge, ruled by no forms of authority other than knowledge itself (Merton, 1942 and 1968).

The making of the bomb marks the beginning of a new kind of modernity. The Manhattan Project essentially imports, digests and assimilates into its metabolism the epitome of Mertonian science, theoretical physics. What comes out it, besides the bomb, is the hybridization of science and technology. In this hybrid form, the quality of scientific knowledge is not determined and assessed within the boundaries of the "republic of science". It is evaluated by the larger community in charge of its technological function, deployment, and impact. New technoscientific enterprises work on an industrial scale and they require specific principles for managing and controlling the quality of their products[9].

In these early stages of hybridization, technological development is granted with the epistemic and moral legitimation of pure science. In November 1945, just after the end of the war, President Roosevelt addresses a letter to the then

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[8] For or a more extensive account, see Benessia and Funtowicz, 2016.

[9] An interesting example of the industrial system of quality control comes from the American engineer and statistician W. Edwards Deming, who introduced in the 1950s the participatory practice of "quality circles" in the world of manufacturing companies. Deming's basic idea was to invite workers in assembly lines to meet regularly for sharing, analyzing and solving work-related issues. Quality circles allowed companies to benefit from the practical knowledge, experience and commitment of the workforce, while encouraging the practice of whistle blowing as an opportunity for early warnings of quality decay. Deming presented the practice of quality circles first in Japan, where he was invited to help in the post war reconstruction effort by the Union of Japanese Scientists and Engineers. His work ended up shaping the efficiency and productivity of Japanese and American industry for the years to come (Deming, 1986).

director of the Office of Research and Development, the American engineer Vannevar Bush – who played a crucial role in the establishment of the Manhattan Project. Roosevelt asks crucial questions about the role of the national government in coordinating scientific and technological development in the transition from war to peace. Bush replies by writing a later famous report, marking the birth of the US National Science Foundation, eloquently titled "Science, the Endless Frontier" (Bush, 1945). From a crucial asset of military defense, basic scientific research becomes the engine of economic growth, through its technological applications. A few years later, the shock of military nuclear technology becomes a promise of free unlimited energy, in the words of President Eisenhower's speech "Atoms for Peace" (Eisenhower, 1953).

Since the early 1960s, the marvels of technoscientific progress begin to manifest their weaknesses. Side effects and unintended consequences gain a prominent seat in the public arena and a self-conscious analysis of science as social activity becomes pressing. In 1963, the British physicist Derek de Solla Price develops the first attempt to measure the quality of scientific research with quantitative indicators (Price, 1963). In a parallel way, popular writings by a whole generation of scientists occupy two decades of civic debate, engendering the emergence of the first environmental movements and the idea of sustainable development: the marine biologist Rachel Carson and the shadows of the Green Revolution (Carson, 1962), the nuclear physicist Alvin Weinberg and the long-term risks of civil nuclear technology[10] (Weinberg, 1972), The Club of Rome and the inherent material limitations to the model of economic growth (Meadows *et al.*, 1972).

Approaching the end of the 1970s, it is painfully clear that uncertainty and complexity cannot be effectively externalized from the realm of technoscientific endeavor, as was so blatantly the case with the making of the first atomic bomb. In 1979, the nuclear accident at Three Miles Island triggers the definition of "normal accidents" by the American sociologist Charles Perrow, referring to the inevitable, built-in vulnerability to collapse of tightly coupled, highly complex technological systems, such as nuclear plants (Perrow, 1984). It is the beginning of the so-called society of risks, as defined in 1986 by German sociologist Ulrich Beck in his later renowned book, capturing the growing awareness that the goods

[10] After many years of service at The Oak Ridge National Laboratory, Weinberg points out that many of the issues arising from the side effects of technology depend on answers to questions "which can be asked of science and yet which cannot be answered by science". These questions are to be defined as trans-scientific: they come from science but quickly transcend it when attempting a response (Weinberg, 1972)

and the bads of technoscientific development are the two sides of the same coin and that risks are woven into the very fabric of technoscientific progress (Beck 1986, 1992).

Uncertainty and complexity even arise in the interplay between the individual and organizational patterns of big enterprises. Based on an extensive set of interviews to the Apollo moon scientists, the American sociologist Ian Mitroff reveals that the most revered and productive researchers at the heart of NASA are the ones that openly manifest individualism, competitiveness and explicit interest biases in their work[11]. Mitroff's work suggests, in detailed and laborious terms, that large technoscientific enterprises, characterized by hierarchical systems and high economic and political stakes, are prone to generating and rewarding a new style of research, complying with the ambivalent *ethos* of technoscientific entrepreneurship (Mitroff, 1974).

With all this in mind, we now approach the beginning of 1986. Feynman is a renowned Nobel Laureate, an admired teacher and public figure.

5. Quality, reliability and safety: the Challenger disaster

"Try playing Russian roulette that way: you pull the trigger and the gun doesn't go off, so it must be safe to pull the trigger again." (Feynman, 1986)

On Tuesday January 28, in a cold winter morning, only three months before the nuclear meltdown of Chernobyl, the NASA space Shuttle orbiter "Challenger" explodes 73 seconds after take-off, live on national TV. The seven crew members on board are killed. With them is the first civilian flying into space, the 37-year-old high school teacher Christa McAuliffe. She was selected from more than 11,000 applicants to participate in the first edition of the NASA Teacher in Space Project, a program designed by President Reagan to engage a disinterested civic society in the wonders of space exploration. Because McAuliffe is on board, the launch and the explosion are broadcasted live in many schools of America, traumatizing an entire generation of students.

A few days later, Feynman receives a call from William Graham, the head of NASA and a former student from the California Institute of Technology[12],

[11] Mitroff explicitly defines a set of counter-norms, at play in dialectical opposition to Mertonian norms: solitariness (vs. communalism), particularism (vs. universalism), interestedness (vs. disinterestedness) and organized dogmatism (vs. organized skepticism).
[12] Where Feynman taught from 1953.

inviting him to join the group in charge of finding the causes of the accident. In a matter of days, President Reagan sets up a Commission, appointing William Rogers, former Secretary of State, as chairman. Feynman is then formally hired with eleven other people. He is the only member on board who has to no ties to NASA or Washington. Not only do they have to "establish the probable causes of the accident" but also "develop recommendations for corrective and other actions based upon the findings and determinations[13]".

As the days and weeks go by, Feynman performs his task with a meticulous and unorthodox investigation, often proceeding on his own. He barely tolerates the formal meetings of the Commission, stretching the rules to privately interview the engineers involved in the program. He even submits anonymous questionnaires to the NASA personnel. As the only outsider, he works as a catalyst of information. He quickly finds out that at least one main part of the Shuttle propulsion system has a known critical issue: the pair of solid-fuel rockets that boost the orbiter at the launch and in the first few minutes of vertical flight. The boosters are made in sections by Morton Thiokol, the manufacturing company in charge of building the components for NASA. They are held together by joints, sealed by a series of rubber O-rings that need to adjust in a few milliseconds to the abrupt change in volume of the booster, when the combustion is ignited and the pressure dilates the various parts of the rockets. In a series of previous flights, the seals have exhibited an erratic behavior, sometimes presenting corrosion and blackening from hot gas burns. Official documents show that the issue has been detected as critical by the engineers, but it has not been addressed (Feynman, 1988).

It is an informal hint from another commissioner, General Donald Kutnya that leads Feynman to find the decisive piece of the puzzle. In a private conversation, the General elliptically mentions that while working on the carburetor of his car in a cold night, he wondered about the effect of temperature on the O-rings (Feynman, 1988)[14]. In the early morning of the launch, the outside temperature was 29° F (-1.6°C) and the lowest temperature of all the previous Shuttle flights was 53°F (11,6 °C). Feynman understands immediately that the issue at stake is the lack of resilience of the rubber O-ring at cold temperatures, compromising the seal and causing a fatal leak of pressurized burning fuel.

[13] From the executive order determining the work of the Commission (Feynman 1988, p.124)

[14] A different version of the story by General Kutnya can be found in "The oral history of the Space Shuttle Challenger Disaster" (Lazarus Dean, 2021).

Frustrated by the lack of speed, precision and accuracy of the assessments on the matter that he has requested from NASA, he realizes that he can test his hypothesis on his own, devising the simplest experiment: squeeze an O-ring with a C-clamp, immerse it in iced water for a few minutes, take it out, remove the C-clamp and measure the time it takes for the O-ring to get back to its original form. After a short trip to a hardware store, he carries out a test in his hotel room in Washington and it works. On the same day, February 11 1986, Feynman does the experiment again, this time live on national TV, during a public hearing of the Commission[15]. The O-ring takes a few seconds to get back to a semblance of its original shape, showing a critical lack of resilience. His memorable performance marks a decisive turn in the investigation, mesmerizing the audience, both in the room and at home. The care for the fundamental physical meaning of phenomena and the modular, bottom up approach that characterizes his style of research since Los Alamos, turn out to be crucial in his contribution as scientific advisor.

Having determined the material origin of the accident, the Commission moves on to examine the issue of causes on a different level, questioning the system of quality control in place at NASA, in charge of the reliability and safety of the machine.

Feynman examines in detail the history of the published criteria for quality certification, the Flight Readiness Reviews, only to conclude that overall system of quality control has been declining over time, becoming dangerously faulty.

The reason behind this process of deterioration can be traced in the unrealistically tight scheduling of the Shuttle flights, needed to keep the space program alive and funded. Because of the rigid time constraints, the management keeps accepting a lower standard of safety from one flight to the next, skipping obviously needed engineering revisions that would imply intolerable delays. Evident signs of faulty systems are not taken into consideration. Once again, quality of knowledge and action depend on their fitness for a purpose. It declines over time because the purpose of maximizing funding (and the chances of funding) slowly but surely takes precedence over the purpose of maximizing the reliability and safety of the vehicle. What the sociologist Mitroff has described as the inherent, ambivalent *ethos* of technoscientific enterprises such as NASA, has drastic consequences, not on the ways in which quality is defined but on its entropic dynamics. In the last episode, we explored the paradoxes of enclosing quality assessments into sealed ethical boxes, to the point of blinding the scientists involved from

[15] https://www.youtube.com/watch?v=raMmRKGkGD4

reflective thinking – and conscience. Here we observe a different kind of quality loss: a gradual decay to the point of catastrophic breakdown, resulting from the ethical friction between competing interests. From outside the box of both NASA and Washington, in this case Feynman has the room to think (about the moral fallacies of others).

6. Quality and integrity: Cargo Cult Science

"… nature can be fooled". (Feynman, 1986)

In his minority report published as Appendix F in the final assessment of the Rogers Commission[16], Feynman points out that the probabilities of failure, i.e., the risk of a fatal accident for the Challenger, are matters of "opinion" at NASA, ranging from roughly 1 in 100 in the accurate estimate of the working engineers, to 1 in 100,000 in the evaluation of the management. Such a "fantastic faith in the machinery" from the working officials is based on a flawed circular logic, in which the absence of failure in previous flights is taken as an argument for the safety of the following ones. In an article published on the New York Times in June of 1986 (Blakeslee, 1986), Feynman writes that the public officials at NASA were essentially "fooling themselves" into believing that such a "magic" way of thinking could be pursued with no consequences, because, as stated at the end of Appendix F, ultimately "nature cannot be fooled" (Feynman, 1986). Feynman refers to the "reality" of natural laws, which "cannot be fooled" by human interests, appealing to the possibility and the necessity of separating (and prioritizing) the facts of science from the values of decision-making, in the name of technological safety. As an inquisitive, curiosity-oriented commissioner in charge of a public investigation, Feynman recognizes the complexities and ambivalences of hybridized technoscience, but he still relies on the possibility of retreating within the boundaries of pure science for ensuring both the True and the Good.

The same colloquial expression that Feynman uses in communicating his findings about the Challenger – fooling and being fooled – is at the center of a commencement speech that he gave at Caltech in 1974. The subject of the talk is the demarcation of science from a specific kind of pseudo-science, which is made to have the appearance of science but is void of meaning. Feynman defines this phenomenon as Cargo Cult Science, referring to the practice of some

[16] Feynman's harsh and open critique of NASA's management system triggers strong opposition within the Commission. When asked to downplay his tone and content, he threatens to withdraw his name from the final report. As a result, his remarks are published as Personal Considerations in an autonomous appendix.

indigenous populations in Malaysia who attempted to summon the presence of military airplanes carrying goods, by mimicking the set up in which they magically appeared during the War – and disappeared after it ended (Feynman, 1974).

Young scientists are not explicitly taught but need to learn by example a special kind of integrity, so they don't fall into the traps of Cargo Cult scientific practices. This form of scientific integrity is not only honesty in the strict sense, but also the willingness of "leaning over backwards" to show that one might be wrong. This can be done only if scientists learn "not to fool themselves" in the first place, so that they don't fool other scientists and the public. "Don't fool yourself" becomes then the fundamental principle of scientific integrity and, as Feynman specifies, it requires special care because "you are the easiest person to fool". The language is different but the idea is analogous to the one expressed in the writings of Hannah Arendt. The 'special care not fool oneself' is the 'ability to think'. The fundamental components of any scientific theory, the *logoi* of research, must hold the pressure of this specific kind of wind of thought, before they can be disseminated into the world. The moral implications of not thinking, of fooling oneself into Cargo Cult scientific practices, can be disastrous.

In the public hearing of February 25 1986, the Rogers Commission collects the testimony of Robert Lund, one of the head managers at Morton Thiokol. Because NASA required a written authorization from Thiokol to confirm the launch, the company played a fundamental role in the decision that led to the catastrophe. In an exchange with Feynman, Lund keeps affirming that they authorized the launch because the role of temperature in compromising the functionality of the seals "was not clear", given that "the data were inconclusive". To which Feynman replies:

> It was clear from the point of view of the engineers. They were explaining *why* the temperature would have an effect. You see, *when you don't have any data you have to use reason*, and they were giving you reasons (Roger Commission hearing, February 25, 1986, italic mine[17]).

When facing ignorance and uncertain knowledge, the search for truth in the form of relevant statistical data has to leave room for the quest for physical meaning, coming from the active and competent reasoning of the engineers at work. The disregard for sound scientific reason in favor of an incongruous use of statistical language from the working officials can be considered as a clear instance of Cargo

[17] See https://www.youtube.com/watch?v=1jPP7Ks6Rhkandt=16973s at 5:02:56. Retrieved on 15.06.2021.

Cult practice, summoning safety by using its lexicogrammar[18]. The correspondent endemic lack of integrity, in this case of first order (moral commitment to tell the truth) and second order (moral commitment to lean over backwards with critical thinking), ends up lowering the quality of the overall system to a point of no return. The explosion of the Challenger is not an accident, but a disaster waiting to happen.

7. Quality and reflexivity: concluding remarks

Traditionally, the quality of scientific knowledge is associated with objective truth, assessed by the few who can speak its language. It is what has kept science in a unique and privileged position to legitimize action since its foundation: the modern ideal of "science speaking truth to power" (Wildasvky, 1972) and power ensuring the common good.

In our brief story, we begin by challenging this modern perspective on the quality of science from within. We have seen that, even in the deep recesses of pure science, in the search for the fundamental and universal laws governing the physical world, scientists' relationship with truth – thus quality – is not a given. What researchers consider as a valuable language and a meaningful theory depends on the theoretical cultures in which they are immersed, on their style of research[19]. As one of the founding fathers of quantum mechanics, Dirac aims at uncovering the universal mathematical laws of nature. The quality of a theory is associated with its universality, formal essentiality (beauty) and metaphysical truth. For Feynman, who learned quantum mechanics as a powerful technique to apply at Los Alamos, mathematical language is a way to understand physical phenomena, to solve problems. He is after empirical truth (Oppenheimer, 1953). This dual perspective on the quality of physical laws is very much alive and contested today. Theoretical physics is colonized for the most part by string theory, a framework that has the potential to unify general relativity and quantum mechanics[20]. Although formally and metaphysically attractive, the field of string theory does not provide clear paths to viable experimental verification. As a result, for many scientists, its epistemic quality is null, as it falls out of falsifiable – thus

[18] For a seminal work on this specific kind of Cargo Cult Science – improper use of quantitative language when facing uncertainty in decision-making processes – see Funtowicz and Ravetz "Uncertainty and quality in science for policy" (Funtowicz and Ravetz 1990).
[19] The French poet René Daumal defines style as "the imprint of what one *is* in what one *does*" (Ferrick Rosenblatt 1999, p.123). While he refers to style within artistic practice, from what we have seen, scientific research is not different in this regard.
[20] The two different theories describe the world on a very big and a very small scale. Both are accurate and yet they cannot be satisfactorily unified into a single framework.

legitimate – science (Popper ,1935). In a phrase attributed to another founding father of quantum mechanics, Wolfgang Pauli, it is "not even wrong" (Ellis 2006 and Woit, 2006).

We then proceeded to show that metaphysical truth becomes irrelevant and empirical truth insufficient as criteria for quality assurance, when curiosity-oriented science is hybridized with technological development, within big techno-scientific enterprises. In this move, the quality of research shifts from the ideal of self-contained objectivity and universality – discovering the laws of nature, describing, and predicting the world of phenomena – to incorporate the realm of subjectivity. "What can be considered as a successful technoscientific enterprise, and for whom? Who can make it, how and why?" become crucial questions. In this context, quality of knowledge and action is pursued, assessed and maintained in terms of fitness for a purpose. As we have seen, this criterion carries some major limitations and pitfalls.

In the first episode, a full success in terms of technological achievement – the making of the atomic bomb – dramatically shows what happens when values are externalized and tight ethical boxes are sealed around a mission. Expressed in binary terms, inside the box, the purpose is fulfilled and the quality of the product of the technoscientific effort is at its top – it works perfectly well. As seen from outside of the box, when the mission is accomplished, it precipitates to zero. The message we can take from looking at Hannah Arendt's work is that, in order for quality to be preserved, a quest for the overall *meaning* of the purpose at stake, in the form of reasoning – of thinking as a self-reflection – has to be present in a parallel way to the intellectual search for (technoscientific) knowledge[21].

In the second chapter of our story, the friction between competing interests within the technoscientific enterprise of NASA – the safety and reliability of the technology on one side and the speed of development of the other – triggers an entropic dynamics in which quality deteriorates to the point of breakdown. Fully immersed in the ideals of modernity, as a scientific advisor, Feynman believes in the possibility of retrieving the quality of research within the boundaries of the Mertonian "republic of science", appealing to its relationship with scientific integrity: basic honesty (commitment to empirical truth) combined with the ability to "leaning over backwards" to show that one might be wrong.

[21] Arendt distinguishes between intellect, in charge of knowing (search for truth) and reason, at the service of understanding (quest for meaning) (Arendt, 1971).

In both cases, a form of critical self-reflection is invoked for the scientists at work, as an antidote to safeguard quality as fitness for purpose from its drawbacks. However, it is not clear how to procure the remedy when needed. In the first episode, Feynman states that as a scientist embedded in the mission, it was impossible to keep reasoning about the meaning of the bomb while making it: the urgency and stakes were so high that the motivations were not negotiable in anyone's conscience. In the second chapter, the retreat to the republic of science that Feynman invokes seems to be unfeasible. As many sociologists of the time were showing, lack of integrity – in the form of contending and ambivalent norms of technoscientific praxis – was not exceptional to the Challenger disaster but somehow inherent in the scale and stakes of big technoscientific endeavors (Mitroff, 1977), leading to an essential impasse in the assurance of quality over long periods of time (Merton, 1984, Beck, 1986).

What then? Some key intuitions to address the preservation of quality in the era of hybridized technoscience come from an article published in The Guardian on May 19, 1986, by Jerome Ravetz, Sally Macgill and Silvio Funtowicz, at the time working together at the University of Leeds (Ravetz *et al.*, 1986). Only one month before the publication, the nuclear disaster of Chernobyl has traumatically shown that not only the United States but also the Soviet Union cannot safely run large and complex technoscientific enterprises. In order for quality assurance to be retrieved, the authors state that not only do scientists have to commit to integrity and prudence on their own terms[22], but, most importantly, they also have to become socially and ethically *accountable*. Facing the collapse of the ideal of expert infallibility and moral autonomy[23], a new social contract of expertise has to be formed: effective public participation in technoscientific policy decisions cannot be delayed. It is the seed of post-normal science, the perspective proposed by Funtowicz and Ravetz in the early 90s to describe the inherent entanglement between facts and values in the interaction between science and policy when decisions are urgent and stakes are high, requiring the extension of participation not only as a moral commitment but as an epistemological need (Funtowicz and Ravetz, 1993).

Combining the insights from our story, the quality of research could thus be pursued and preserved over time when the aims, motivations and possible consequences of technoscientific endeavors are constantly negotiated through a form of collective reasoning (thinking as a self-reflection) – "leaning over backwards" to show how we all might be factually and/or ethically wrong. Quality

[22] Like integrity, also prudence entails a self-reflecting attitude.
[23] Defined as the Ch/Ch Syndrome (Challenger / Chernobyl) (Ravetz *et al.*, 1986).

then becomes strictly related to a form of shared reflexivity, of "self-awareness of action within a system (ecosystem)" (Funtowicz and O' Connor, 1999).

These quite abstract principles can become useful to address the demands for quality of (scientific) research that emerged in our gathering in 2019 and are most relevant in current times. Exemplifying a possible path of investigation, we could begin a process of self-reflection on our own *ethos* and *praxis* of research, by exploring the theoretical culture in which we are embedded, the methods we are accustomed to valuing, the kinds of questions we are prone to ask, our relationship with truth. Is our style of research the result of external binding conditions or is there room to express our own early inner aspirations and modes of being in the world? We could then move to investigate the aims, motivations and possible outcomes of our professional endeavours, integrating our search for knowledge with a quest for meaning. A special kind of attention could be given to the kind of language and knowledge we use. Are they adequate to answer the questions that we value as relevant? Do they need to be conversing with other kinds of language and knowledge? Most importantly: who is included in the use of "we"? Who is comprised among human beings? And who is involved among non-humans[24]?

Finally, besides mere honesty, are we willing to lean over backwards to show how we might be wrong, or simply blind? At what cost?

Asking these kinds of questions sets in motion (*ar*) a wind of thought, clearing the room for a plurality of ways of living and knowing to be explored, hopefully awaking new forms of wisdom and collective awareness.

In the writing of the American author Robert Pirsig:

> Quality is not a thing. It is an event. […] Quality is the event at which awareness of both subjects and objects is made possible (Pirsig, 1974).

As such, quality is not an asset to be found, produced or managed, but a correspondence between inner and outer world, to be summoned and nourished through persistent conscious work.

[24] For a first exploration on this crucial issue, see De Sousa Santos, 2007 and David Waltner-Toews, 2020.

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